

Resonant Tunneling Spectroscopy of Interacting Localised States

– Observation Of The Correlated Current Through Two Impurities

V.V.Kuznetsov^(*), A.K.Savchenko

Department of Physics, Exeter University, Stocker Road, Exeter EX4 4QL, United Kingdom

D.R.Mace, E.H.Linfield, and D.A.Ritchie

Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, United Kingdom

(February 1, 2008)

Abstract

We study effects of Coulomb interactions between localised states in a potential barrier by measuring resonant-tunneling spectra with a small bias applied along the barrier. In the ohmic regime the conductance of $0.2\mu\text{m}$ -gate lateral GaAs microstructures shows distinct peaks associated with individual localised states. However, when an electric field is applied new states start contributing to the current, which becomes a correlated electron flow through two interacting localised states. Several situations of such correlations have been observed, and the conclusions are confirmed by calculations.

PACS Numbers: 73.20.Dx, 73.40.Gk, 73.40.Sx

Resonant-tunneling (RT) spectroscopy is a well known technique for the study of localised states in a potential barrier¹. Its essence is in the measurements of the conductance in a transistor microstructure where the barrier height is controlled by the gate voltage, V_g . With changing V_g localised levels are moved with respect to the Fermi level in the contacts and a conductance resonance occurs when a state passes the Fermi level. It has been usually assumed that there is no Coulomb interaction between the states, which is only justified if they are well separated along the barrier width W , Fig.1a. Otherwise the energy resonance of a state will depend on the occupancy of the neighbouring states. When level i is occupied, it will shift level j upwards by the Coulomb energy $U_{ij} \approx e^2/\kappa r_{ij}$, where r_{ij} is the separation between the two impurities and κ is the dielectric constant. We demonstrated that in GaAs structures with a doping of 10^{17} cm^{-3} and a gate length of $0.2\mu\text{m}$ there is a high enough probability for several impurities to be close to each other and interact². These experiments were performed by measuring RT spectra in the ohmic regime and suggested that, due to the Coulomb shifts of three interacting impurities, one level can exhibit two resonances in $G(V_g)$.

In this work on the same type of structure we have found direct manifestation in the RT spectra of the Coulomb interaction between two localised states – a correlated current through two impurities. When a small bias V_{sd} is applied to the barrier, two interacting states can only carry the current in a correlated way: at the times when one level is occupied the other level is lifted up and switched off from conduction.

There have been intensive theoretical studies of tunneling through a mesoscopic barrier containing interacting states^{4–6}, with several suggested models of the correlated current through two energy levels. In the situation where these levels were two different-spin states of the same impurity there was a prediction that the averaged conductance of a macroscopic barrier with many states should decrease with magnetic field⁵. This effect was observed in the hopping magnetoconductance of large-area αSi barriers⁷. For a small-area barrier containing two impurities current-voltage characteristics were calculated for the case when electrons sequentially tunnel through the two impurities⁶. Here we present experimental results on mesoscopic GaAs barriers where the current through a few localised states is measured as a function of V_g at different biases V_{sd} . This allows one to separate the contributions of the impurities to the current. The results, confirmed by the calculations, show that we are dealing with several situations of the correlated current through two interacting impurities which conduct in parallel.

Fig.1a shows the cross-section of our system, a metal-semiconductor field effect transistor (MESFET), which is a doped GaAs layer of $0.15\mu\text{m}$ thickness, MBE grown on an insulating substrate, with a short metal gate on the surface of the wafer. Due to depletion under the gate, a lateral barrier is formed in a doped layer and its height is controlled by a negative voltage between the gate and the 'source'-contact. Outside the gate area, conduction has metallic-like character due to the high concentration of Si dopant (10^{17} cm^{-3}). The differential conductance between the source and drain was measured as a function of V_g , using an AC lock-in technique, at different DC source-drain voltages, V_{sd} . The measurements were performed in a dilution refrigerator where the temperature of electrons in the sample was $\approx 100\text{mK}$.

Consider an energy level which is moved downwards with increasing V_g , Fig.1b. With a source-drain bias applied to the barrier the level will show two resonances in the differential

conductance $dI/dV_{sd}(V_g)$, namely at μ_l and μ_r – the energies where the current is switched ‘on’ and ‘off’. The two resonances will form a cross– like picture if $dI/dV_{sd}(V_g)$ –dependences are plotted with offsets for different V_{sd} (upwards for positive and downwards for negative biases), Fig.1b. For both polarities of the bias, in the region to the left of the cross the state is positioned below the lowest of the two Fermi levels and is occupied at zero temperature, and in the region to the right of the cross it is empty. In the strip of width eV_{sd} between the two Fermi levels the state is positioned against occupied states in one contact and empty states in the other and hence conducts the current. In $dI/dV_{sd}(V_g)$ the conducting energy strip corresponds to the area between the lines of the cross.

For non-interacting states one would expect a RT spectrum with a simple superposition of their crosses which are shifted along the V_g –scale in accordance with the resonances of these states at $eV_{sd} = 0$. However, the experimental picture shown in Fig.2a is different. Three resonances: at $V_g = -1.8233V$, $-1.8215V$ and $-1.815V$ are seen in the ohmic regime. These resonances correspond to RT through one impurity since a specific feature of RT through two impurities³ is a strong suppression of the peak in dI/dV_{sd} by an electric field with a negative differential conductance, which is not the case in the figure. As expected, the resonances form the corresponding crosses when a V_{sd} is applied. In addition to the main lines of the crosses, however, some extra lines are also seen in the figure. Let us concentrate on the resonance at $V_g = -1.8215V$ and call the localised state which gives rise to this resonance the ‘first’ impurity. The additional lines appearing in its cross manifest two other energy states which start contributing to the current only when a bias is applied. A characteristic feature of these extra lines is that they only exist *within* the cross, when the first impurity carries the current. Extrapolation of these lines shows no resonance at their intercept with the V_g –axis which means that in the ohmic regime, when the first impurity is either empty or occupied, these states have their resonances elsewhere in V_g . Another feature of the additional states needs an explanation: one state contributes to the current primarily at a positive bias (at the top part of the graph) while the other is only seen at a negative bias.

Similar extra lines have been seen in single–quantum dot structures and interpreted as being due to the excitation levels of the quantum dot⁸. In our case the extra lines are shifted with respect to the main lines by $\Delta V_g \approx -0.82mV$ and $\Delta V_g \approx 0.72mV$. This corresponds to $-205\mu eV$ and $180\mu eV$ in the energy scale for the rate of the Fermi level movement $\alpha = d\mu/deV_g \approx 0.2$, Ref.3. This separation is much smaller than one would expect for the separation between the ground state and excited states of an isolated donor, $\Delta\varepsilon \approx 4meV$, and we attribute the extra lines to two separate impurities, ‘second’ and ‘third’, which are positioned close to the first impurity.

When all three impurities are empty at small V_g they are close to each other in energy: level 3 is below level 1 by $205\mu eV$ and level 2 is above level 1 by $180\mu eV$, Fig.2b. Consider how these energy levels are affected in the ohmic regime when the impurities become charged. Suppose a ‘normal’ sequence of events, when impurities are charged one by one and no re–entrant resonance occurs when an occupied level is lifted up and becomes empty again². When the Fermi level is raised and the third (lowest) level becomes occupied it lifts levels 1 and 2 up by $U_{31} \approx e^2/\kappa r_{31}$ and $U_{32} \approx e^2/\kappa r_{32}$, respectively. With V_g increasing further level 1 then becomes occupied and lifts up level 2 by another shift, $U_{12} \approx e^2/\kappa r_{12}$. As a result in the ohmic regime the resonances due to the three levels are well separated in V_g , Fig.2b.

Indeed, for the interaction not to be screened by the metallic gate, the distances r_{ij} between the impurities have to be within $\approx 1000 \text{ \AA}$, which is the distance between the gate and the conducting channel. This gives $U_{ij} \approx 1 \text{ meV}$ and $\Delta V_g \approx 5 \text{ mV}$ – a much larger shift than the separation between the main and the extra lines in Fig.2a.

However, when a bias is applied and impurity 1 carries the current, it is only *partially* empty and occupied. At the times when it is occupied it lifts level 3 up and brings it back into the vicinity of level 1. Then level 3 comes into the conducting energy strip where it can also carry the current. At other times, when level 1 is empty, level 2 comes down from its remote resonance and also starts conducting. Therefore, in the area between the two lines of the cross, levels 3 and 2 carry the current in correlation with the occupancy of the the first impurity.

To explain why level 2 is only seen at a negative bias, let us calculate the current through two interacting impurities, 1 and 2. At $V_{sd} = 0$ the shape of the $G(V_g)$ peaks in Fig.2a is well described by a Lorentzian which is smeared by the Fermi distribution in the contacts with an effective temperature of $\approx 100 \text{ mK}$:

$$G(V_g) = \frac{e^2}{h} \frac{\Gamma_l \Gamma_r}{\Gamma_l + \Gamma_r} \frac{\text{sech}^2((\varepsilon_i - \mu)/2k_B T)}{4k_B T} \quad (1)$$

where $\Gamma_{l,r} \sim E_0 \exp(-2r_{l,r}/a)$ are the leak rates from the impurity to the left and right contacts respectively, $r_{l,r}$ are the distances from the impurity to the contacts, E_0 is the ionisation energy and $a \approx 100 \text{ \AA}$ is the localisation radius. For the peaks in Fig.2 the smallest of the two Γ 's is $\approx 0.1 \mu\text{eV}$ while the largest is less than $10 \mu\text{eV}$. As the temperature smearing is smaller than the level separation, $k_B T \ll \Delta\varepsilon_{12}$, but larger than the width of the resonance, $k_B T \gg \Gamma$, the kinetic equations can be used to calculate the average occupancy of the two impurities $\langle n_1 \rangle$ and $\langle n_2 \rangle$, in a similar way as is done for an impurity with two levels in Ref.4. For a large Coulomb shift, $U_{12} \gg \Delta\varepsilon_{12}, |eV_{sd}|$, the two impurities cannot be occupied simultaneously and $\langle n_1 n_2 \rangle = 0$. Then:

$$\begin{aligned} \frac{d\langle n_1 \rangle}{dt} &= \Gamma_l^{(1)} \left(f_l^{(1)} \langle (1 - n_1)(1 - n_2) \rangle - (1 - f_l^{(1)}) \langle n_1(1 - n_2) \rangle \right) \\ &+ \Gamma_r^{(1)} \left(f_r^{(1)} \langle (1 - n_1)(1 - n_2) \rangle - (1 - f_r^{(1)}) \langle n_1(1 - n_2) \rangle \right), \end{aligned} \quad (2)$$

$$\begin{aligned} \frac{d\langle n_2 \rangle}{dt} &= \Gamma_l^{(2)} \left(f_l^{(2)} \langle (1 - n_1)(1 - n_2) \rangle - (1 - f_l^{(2)}) \langle n_2(1 - n_1) \rangle \right) \\ &+ \Gamma_r^{(2)} \left(f_r^{(2)} \langle (1 - n_1)(1 - n_2) \rangle - (1 - f_r^{(2)}) \langle n_2(1 - n_1) \rangle \right), \end{aligned} \quad (3)$$

where $f_{l,r}^{(1,2)}$ are the distribution functions in the left and right contacts at the levels $\varepsilon_1, \varepsilon_2$. Solving these equations in a steady state gives the expressions for $\langle n_{1,2} \rangle$ in terms of the occupancies of the two states without Coulomb interaction $\nu_{1,2}$:

$$\langle n_{1,2} \rangle = \nu_{1,2} \frac{1 - \nu_{2,1}}{1 - \nu_{1,2} \nu_{2,1}}, \quad (4)$$

where

$$\nu_{1,2} = \frac{\Gamma_l^{(1,2)} f_l^{(1,2)} + \Gamma_r^{(1,2)} f_r^{(1,2)}}{\Gamma_l^{(1,2)} + \Gamma_r^{(1,2)}}. \quad (5)$$

The total current through the two levels is given by

$$I = \frac{e}{h} \Gamma_l^{(1)} \left(f_l^{(1)} \langle (1 - n_1)(1 - n_2) \rangle - (1 - f_l^{(1)}) \langle n_1(1 - n_2) \rangle \right) \\ + \frac{e}{h} \Gamma_l^{(2)} \left(f_l^{(2)} \langle (1 - n_1)(1 - n_2) \rangle - (1 - f_l^{(2)}) \langle n_2(1 - n_1) \rangle \right), \quad (6)$$

and after simplification

$$I = \frac{e}{h} (1 - \langle n_2 \rangle) \frac{\Gamma_l^{(1)} \Gamma_r^{(1)}}{\Gamma_l^{(1)} + \Gamma_r^{(1)}} (f_l^{(1)} - f_r^{(1)}) + \frac{e}{h} (1 - \langle n_1 \rangle) \frac{\Gamma_l^{(2)} \Gamma_r^{(2)}}{\Gamma_l^{(2)} + \Gamma_r^{(2)}} (f_l^{(2)} - f_r^{(2)}) \quad (7)$$

The correlated current in Eq.(7) is different from the current through two non-interacting impurities by the coefficients $(1 - \langle n_2 \rangle)$ and $(1 - \langle n_1 \rangle)$. They reflect the condition that one level can only carry the current if the other level is empty. If the two impurities have a similar position along the barrier length, that is $\Gamma_{l,r}^{(1)} = \Gamma_{l,r}^{(2)} = \Gamma_{l,r}$, their occupancies are also equal, $\nu_1 = \nu_2 = \nu$, and the current becomes

$$I = \frac{e}{h} \frac{2}{(1 + \nu)} \frac{\Gamma_l \Gamma_r}{(\Gamma_l + \Gamma_r)}, \quad (8)$$

As a result the value of the correlated current is controlled by the occupancy ν , which depends on the position of the impurities along the barrier and also on the sign of the applied bias. Suppose that the two impurities are positioned closer to the left contact, Fig.3a, so that $\Gamma_l \gg \Gamma_r$. Then $\nu \approx 1$ for a positive bias from Eq.(5), as the states are then close to the contact with occupied states at energies $\varepsilon_{1,2}$. The current through two impurities in this case, Eq.(8), is not different from the current through only one impurity. Therefore, when with increasing V_{sd} level 2 comes to the conducting strip it does not change the total current and no extra line occurs in the differential conductance. A positive bias corresponds to strong correlations between the two impurities when electrons on them have a long 'waiting' time before they leave to the right contact.

For a negative bias electrons have a short waiting time, $\nu \approx 0$, as the impurities are now close to the empty contact and the correlations are weak. The current through two impurities is twice that for level 1, Eq.(8), and an extra line in dI/dV_{sd} appears in the first-impurity cross at a negative bias.

For correlations between the currents through impurities 1 and 3 in Fig.3b, the situation is the inverse as level 1 has to be occupied for level 3 to be brought into the conducting energy strip. For these impurities being closer to the left contact an increase in the current occurs when correlations are strong, that is for a positive bias.

In Fig.4a another experimental result is presented, where for a negative bias the appearance of a new state within the cross is accompanied by the simultaneous suppression of a main line of the cross and a region of negative differential conductance. To explain such a decrease in the total current caused by level 2, consider a situation when two correlated impurities carry different currents. Suppose that level 2 is closer to the right contact,

$\Gamma_r^{(2)} \gg \Gamma_l^{(2)}$, while level 1 is close to the centre of the barrier, $\Gamma_l^{(1)} = \Gamma_r^{(1)}$. The results of calculations for such a situation, based on Eq.(7), are presented in Fig.4b and show a good agreement with the data in Fig.4a. The effect can be explained as follows. The current through an impurity is limited by the smallest of its leak rates Γ_r and Γ_l , and it is much smaller for level 2 than for level 1. This is why the total current does not change significantly when level 2 appears in the conducting strip at positive biases when correlations are weak for this configuration of impurities and no extra line is seen there. However, the low conducting level can block the current through the highly conductive level in the case of strong correlations at a negative V_{sd} . Then level 2, which is closer to the filled contact, is occupied for a longer time, $\nu_2 \gg \nu_1$, and it lifts level 1 up and decreases the total current.

In conclusion, we have presented the first demonstration of the correlated conduction through two localised states in the parallel resonant–tunneling channels. By studying RT spectra of localised states with a small bias along the barrier, we have directly shown that two levels, which are separated by a Coulomb shift when one is fully occupied, can still conduct in a correlated way.

We thank M.Raikh for reading the manuscript and valuable comments.

(*) Present address: Department of Physics, State University of New York, Stony Brook, NY 11794.

REFERENCES

- ¹ A.B.Fowler, G.L.Timp, J.J.Wainer, and R.A.Webb, Phys.Rev.Lett. **57**, 138 (1986); T.E.Kopley, P.L.McEuen, and R.G.Wheller, Phys.Rev.Lett. **61**, 1654 (1988).
- ² V.V.Kuznetsov, A.K.Savchenko, M.E.Raikh, L.I.Glazman, D.R.Mace, E.R.Linfield, and D.R.Ritchie, Phys.Rev. **B54**, 1502 (1996).
- ³ A.K.Savchenko, V.V.Kuznetsov, A.Woolfe, D.R.Mace, M.Pepper, D.R.Ritchie, and G.A.C.Jones, Phys.Rev. **B52**, R17021 (1995).
- ⁴ T.K.Ng and P.A.Lee, Phys.Rev.Lett. **61**, 1768 (1988); L.I.Glazman and M.E.Raikh, JETP Lett. **47**, 453 (1988); Y.Meir, N.S.Wingreen, P.A.Lee, Phys.Rev.Lett. **66**, 3048 (1991); S.Hershfield, J.H.Davies, and J.W.Wilkins, Phys.Rev.Lett. **67**, 3720 (1991); Y.Meir, N.S.Wingreen, Phys.Rev.Lett. **68**, 2512 (1992).
- ⁵ L.I.Glazman and K.A.Matveev, JETP Lett. **48**, 445 (1988).
- ⁶ M.Raikh and A.Asenov, Superlatt. and Microstr. **11**, 325 (1992).
- ⁷ D.Ephron, Y.Xu, and M.R.Beasley, Phys.Rev.Lett. **69**, 3112 (1992).
- ⁸ A.T.Johnson, L.P.Kouwenhoven, W. de Jong, N.C. van der Vaart, and C.J.P.M.Harmans, Phys.Rev.Lett. **69**, 1592 (1992); J.Weis, R.J.Haug, K.v.Klitzing, and K.Ploog, Phys.Rev.Lett. **71**, 4019 (1993); D.Weinmann, W.Hausler, and B.Kramer, Phys.Rev.Lett. **74**, 984 (1995).

FIGURES

FIG. 1. a) Sketch of the geometry of the conducting channel between two ohmic contacts in a GaAs MESFET, showing the position of a short barrier and three impurities in it. The gate length (along the current) L equals $0.2\mu m$ and width W equals $20\mu m$. b) Schematic diagram of the potential barrier with a positive and negative bias applied. The differential conductance as a function of gate voltage shows a 'cross' when plotted with an offset for different V_{sd} (upwards for a positive bias). The area between the two resonances corresponds to the impurity carrying current and being partially occupied.

FIG. 2. a) Logarithm of the differential conductance as a function of gate voltage at $T = 100mK$ shown with a conductance threshold of $0.01\mu S$. Curves for different V_{sd} , changed with a step of $16.4\mu V$, are offset (upwards for a positive V_{sd} with respect to the ohmic regime shown by the highlighted curve). b) Three interacting localised states with close energies when not occupied. A diagram of the first impurity cross with the extra lines within it due to impurities 2 and 3. In the ohmic regime the resonances of these impurities are separated from the first-impurity resonance, but with a V_{sd} applied they are brought into its vicinity.

FIG. 3. Calculations of the differential conductance for correlated tunneling through two impurities: a) 1 and 2, b) 1 and 3. The highlighted curves correspond to $V_{sd} = 0$ and curves for different V_{sd} , which is changed with $\Delta V_{sd} = 15\mu V$, are offset. Parameters: $kT = 10\mu eV$, $\Delta\varepsilon_{12} = \Delta\varepsilon_{13} = 230\mu eV$, $\Gamma_l^{(1)} = \Gamma_l^{(2)} = 1\mu eV$, $\Gamma_r^{(1)} = \Gamma_r^{(2)} = 0.1\mu eV$, $\beta = d\varepsilon_i/deV_{sd} = 0.25$, $\alpha = 0.26$. Inserts show configurations for strong ($\nu = 1$) and weak ($\nu = 0$) correlations.

FIG. 4. a) Negative differential conductance occurring at a negative V_{sd} , $T = 100mK$. The curves are measured with a step ΔV_{sd} of $50\mu V$. b) Calculation of the differential conductance with parameters: $kT = 10\mu eV$, $\Delta\varepsilon_{12} = 230\mu eV$, $\Gamma_l^{(2)} = 0.01\mu eV$, $\Gamma_r^{(2)} = 5\mu eV$, $\Gamma_l^{(1)} = \Gamma_r^{(1)} = 0.5\mu eV$, $\beta = d\varepsilon_i/deV_{sd} = 0.4$, $\alpha = 0.2$, step $\Delta V_{sd} = 50\mu V$.

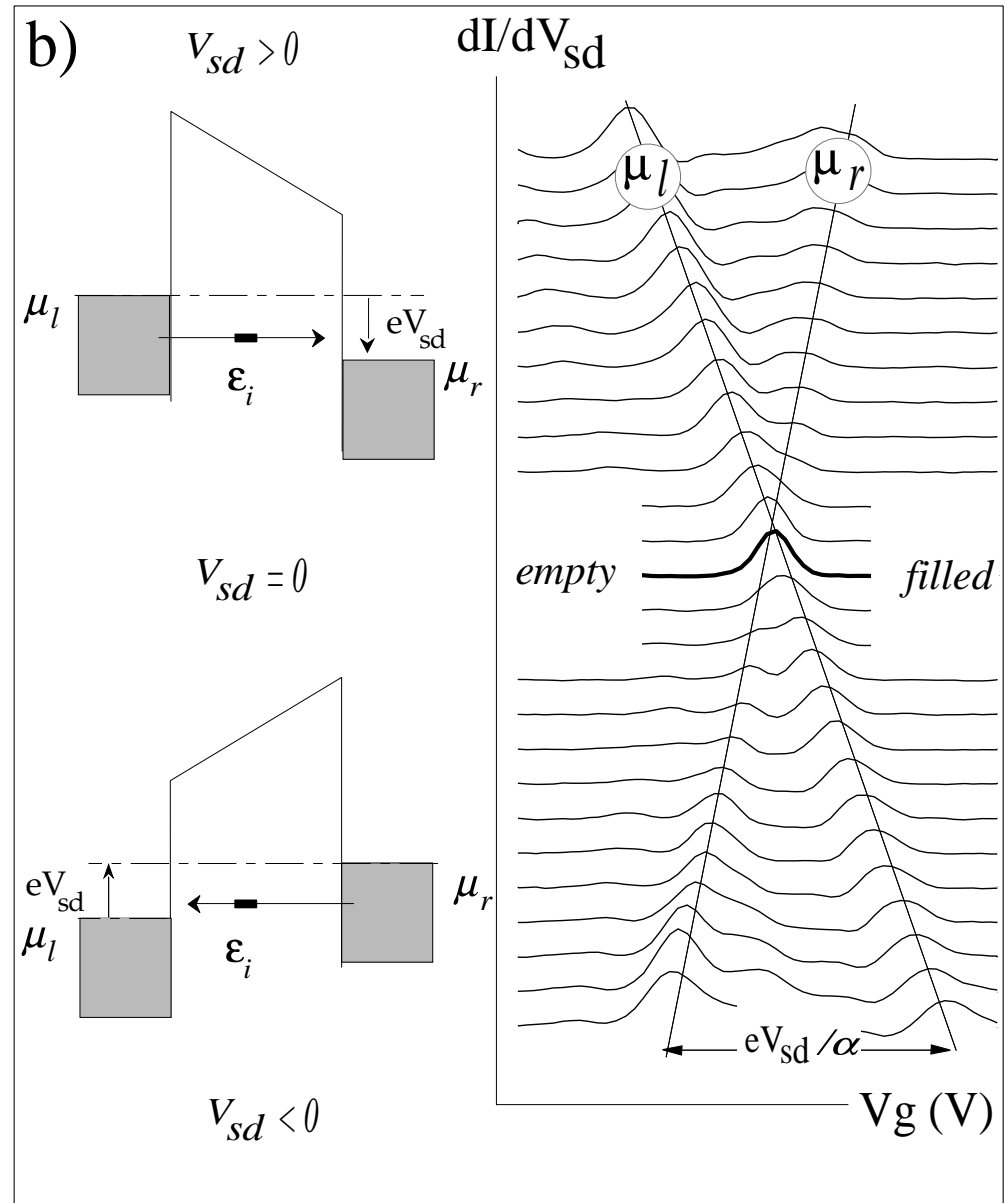
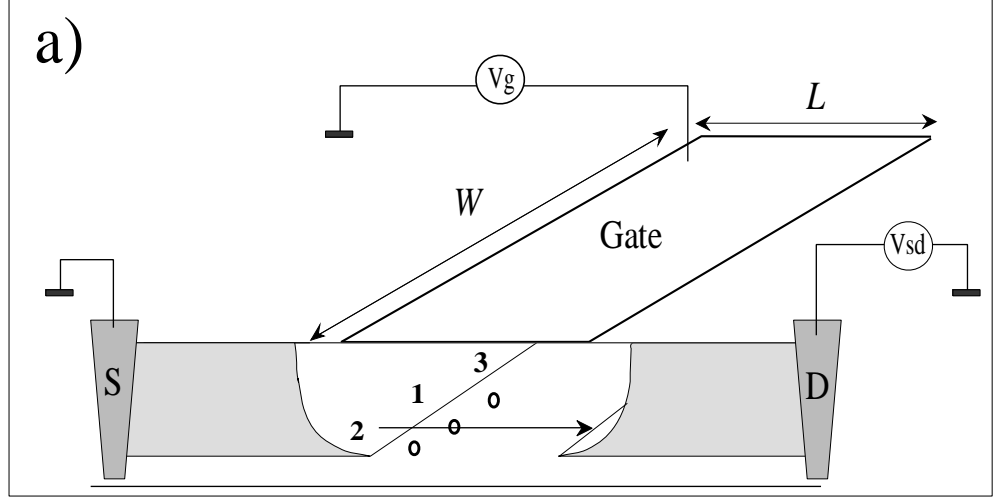


Fig. 1

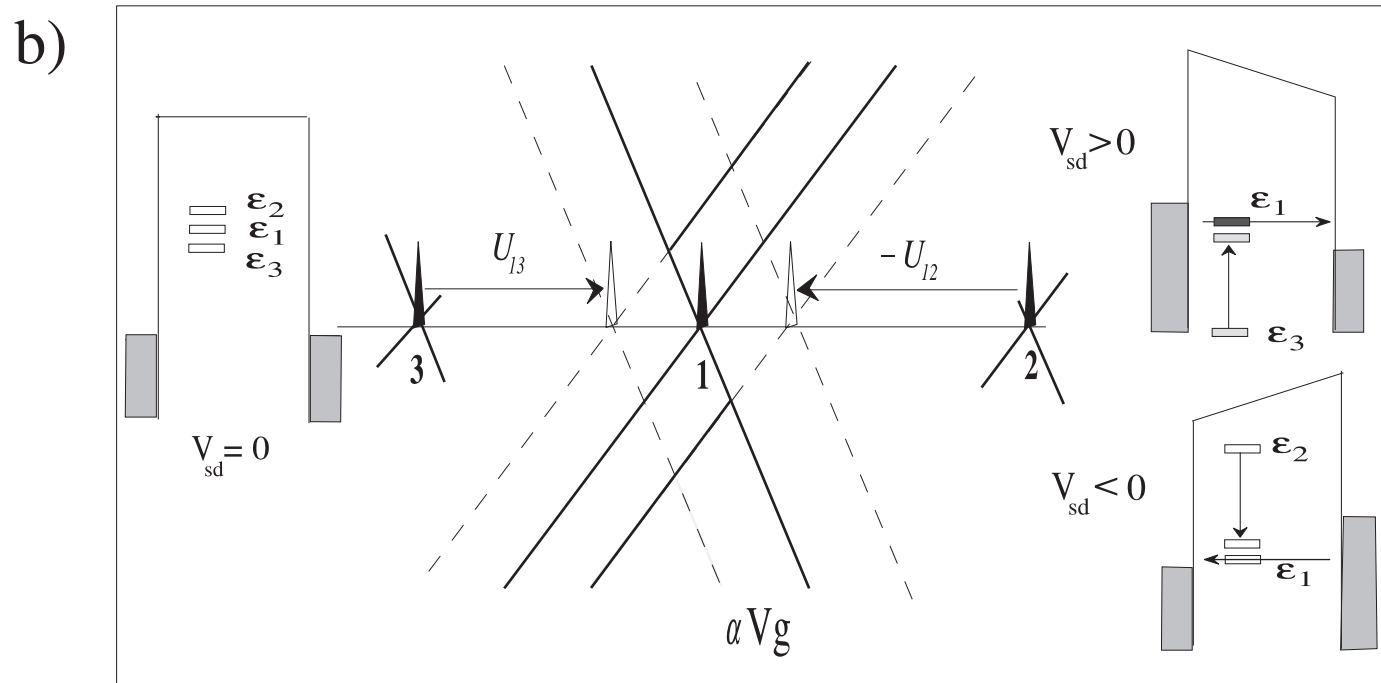
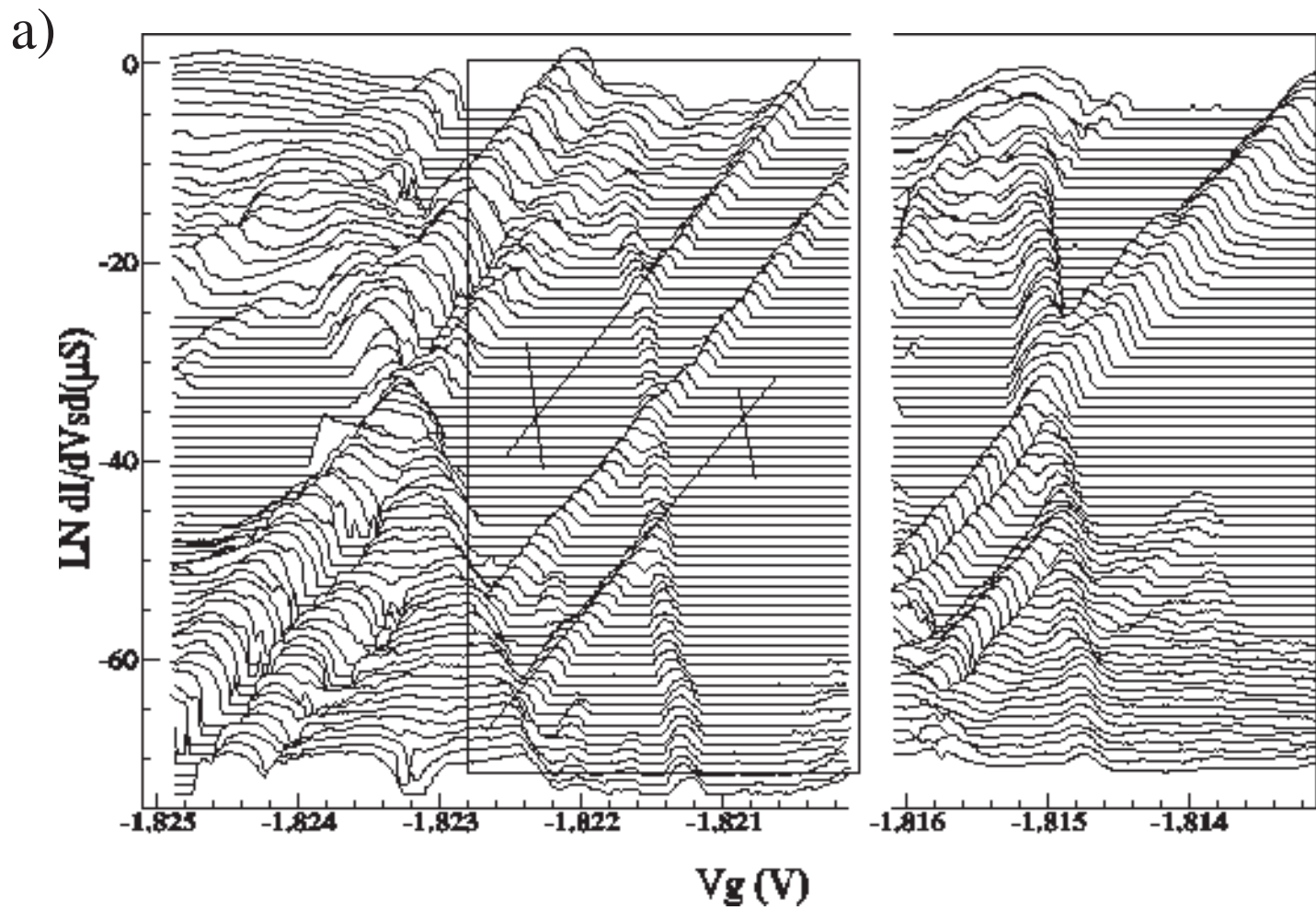


Fig.2

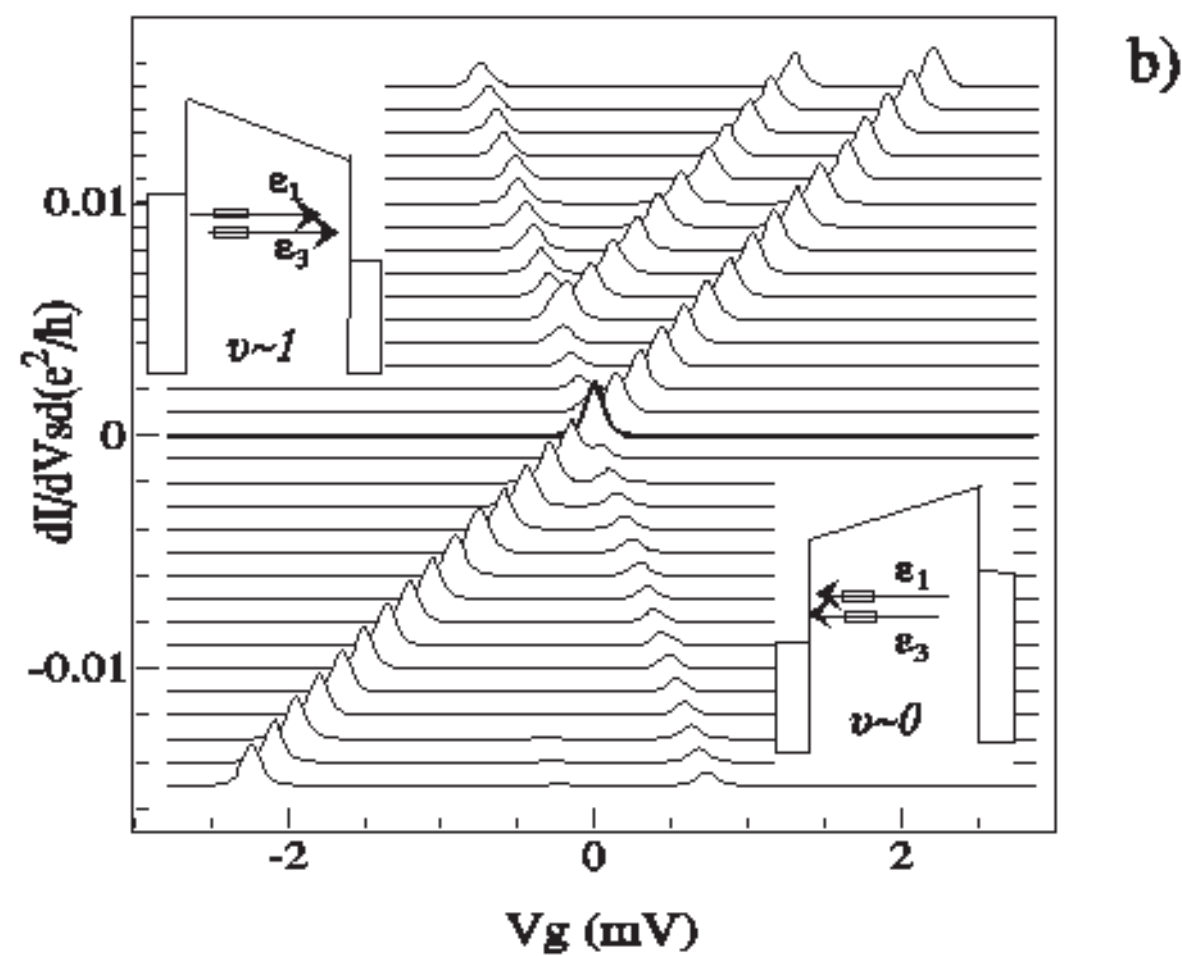
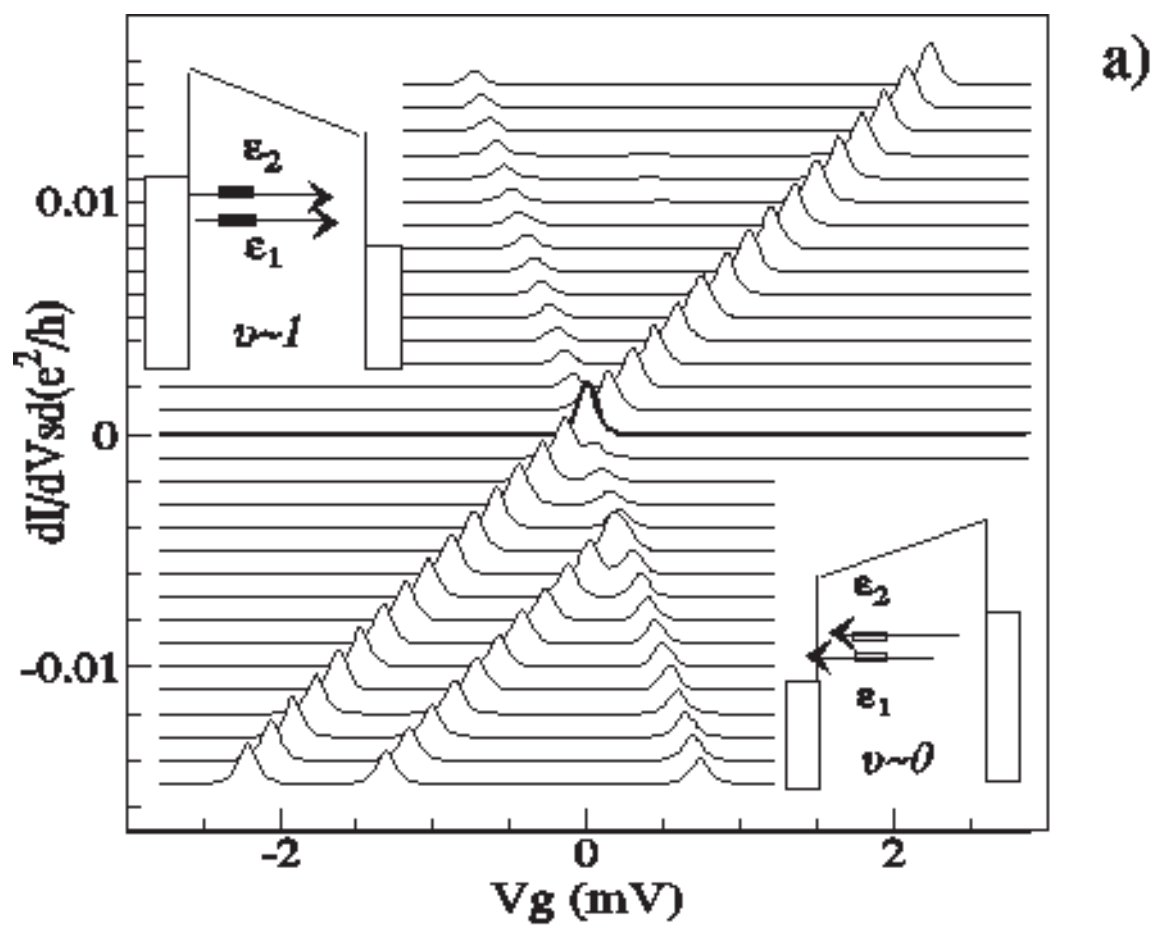
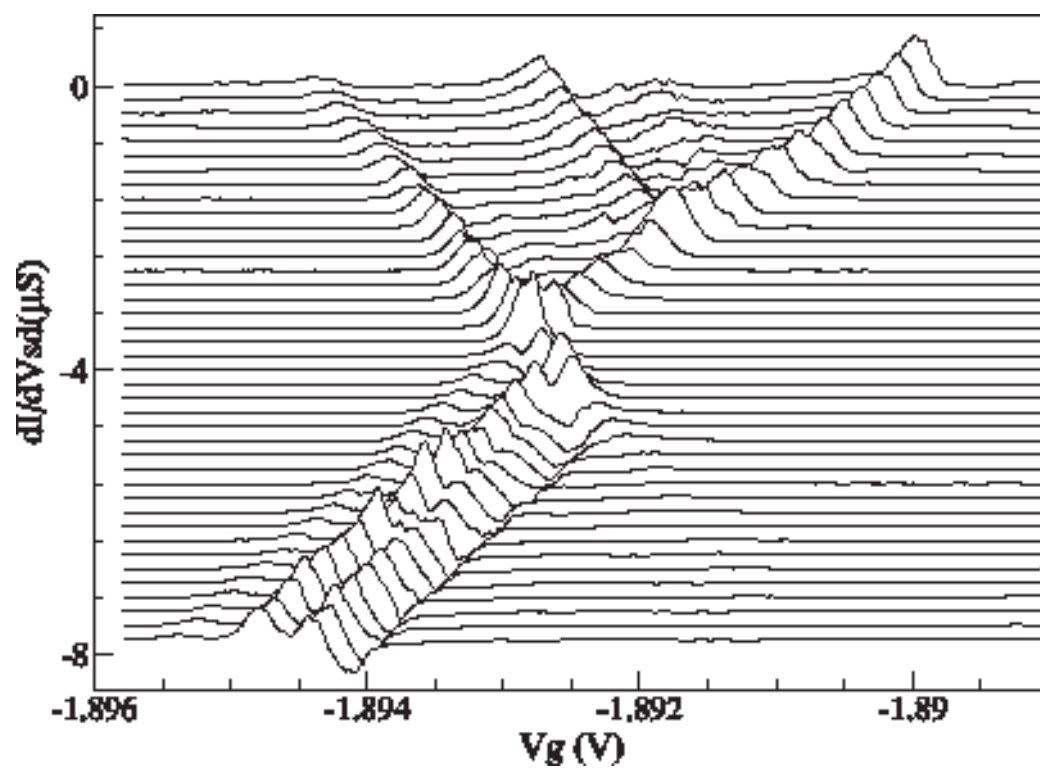


Fig.3

a)



b)

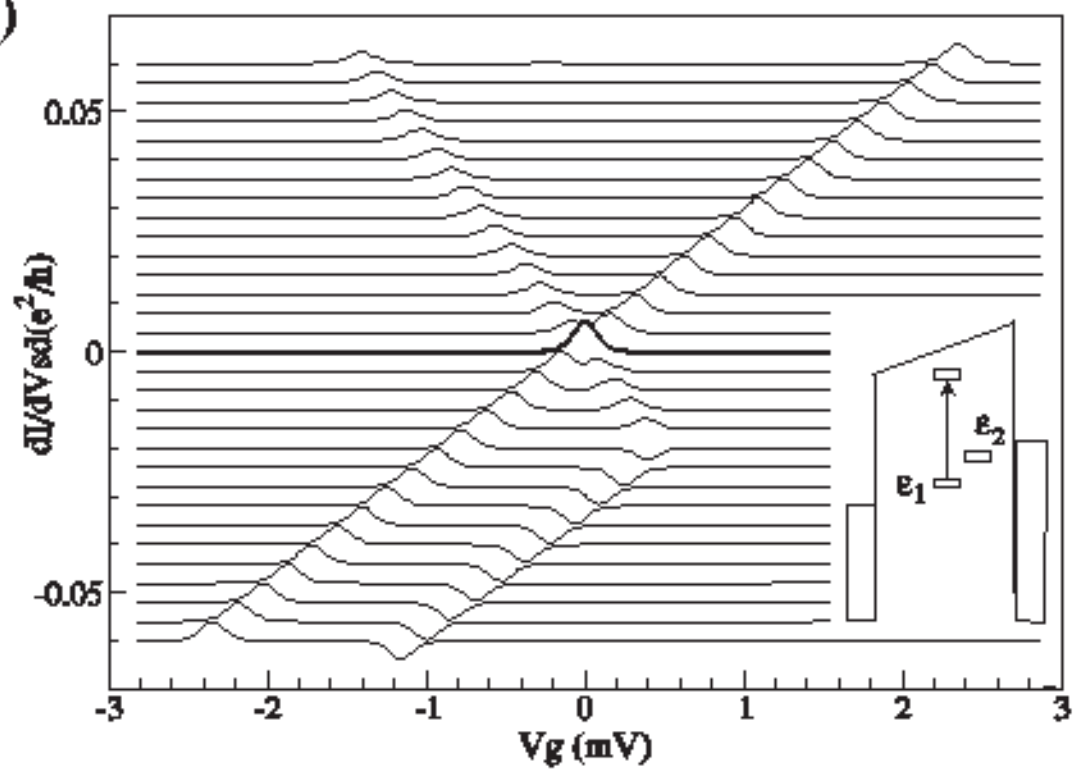


Fig.4